Low Energy RHIC electron Cooling (LEReC)

LEReC overview: project goal and cooling approach

Alexei Fedotov

C-AD Machine Advisory Committee Meeting
8 – 10 December 2014

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

- Low Energy RHIC Physics Program
- Luminosity improvement with electron cooling
- LEReC scope
- Cooling parameters
- Cooling approach
- Challenges
- Project timeline
- Summary

LEReC reviews

- **Accelerator Physics Review, August 13-14 2013:**

http://www.c-ad.bnl.gov/ardd/LEeC/default.htm

Report and talks are available. Many reviewed accelerator topics stayed the same.

- January 2014: Due to cost constraints baseline was changed from new 100 MHz SRF gun to already existing 704MHz SRF gun which is presently under commissioning.

- **DOE Technical, Cost, Schedule and Management Review, July 9-11, 2014:**

https://indico.bnl.gov/event/LEReCReview2014

- November 2014: Following DOE recommendations, parallel path with DC photoemission gun (contract with Cornell in process) started. SRF gun commissioning will continue.

LEReC MAC presentations

Low-Energy RHIC electron Cooling (LEReC)

10:40 LEReC overview – goals and cooling approach: A. Fedotov (35+10 min)

11:25 SRF Gun Commissioning Progress: Wencan Xu (20 min)

11:45 LEReC Beam dynamics simulations J. Kewisch (20+10 min)

12:15 Lunch - Small Conference Room

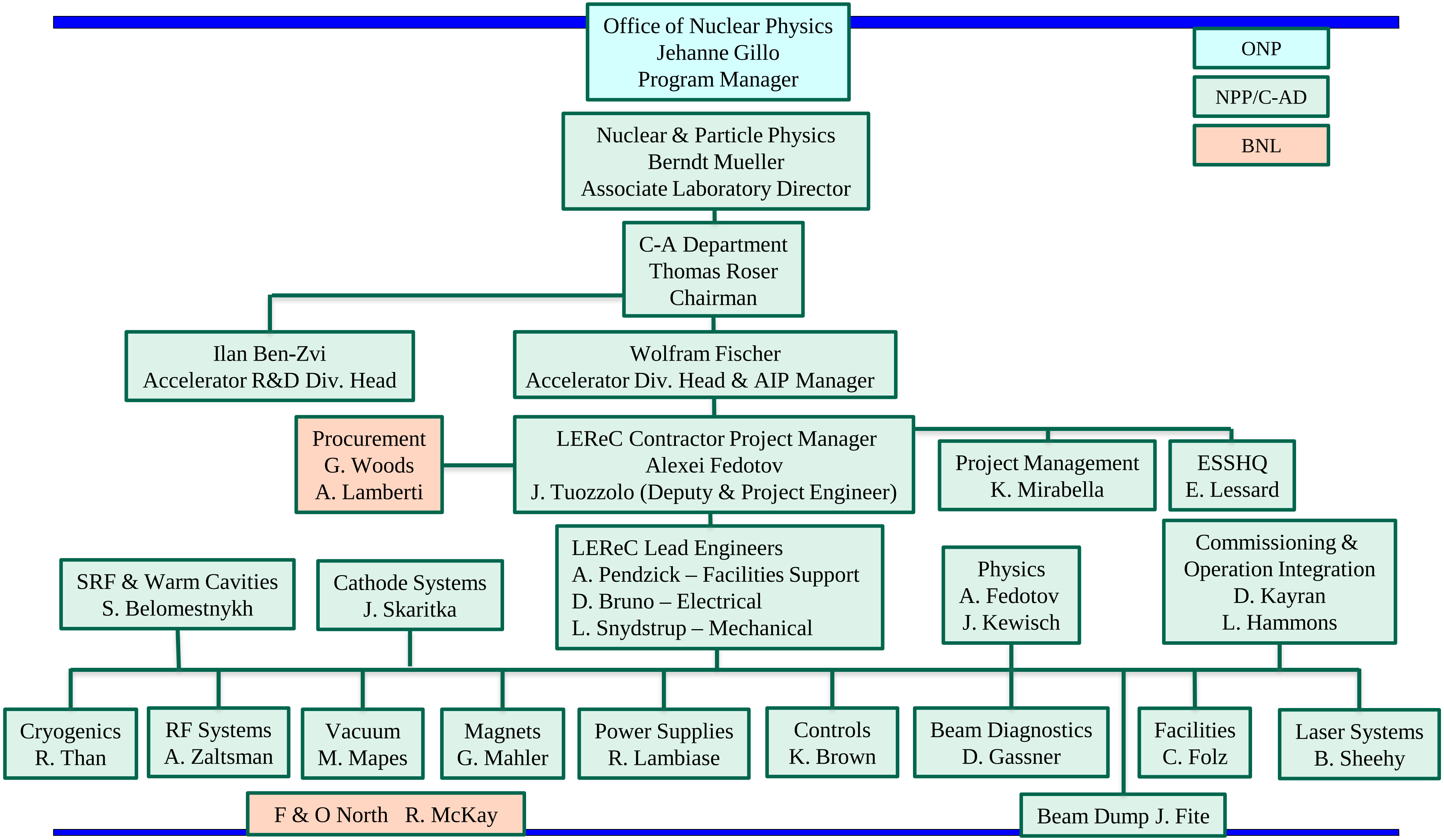
13:00 Tour IR2 – Location of LEReC and CeC PoP

14:30 System engineering design, construction, and installation J. Tuozzolo (30+10 min)

15:10 SRF and warm RF components S. Belomestnykh (20+10 min)

15:40 Instrumentation D. Gassner/T. Miller (20+10 min)

LEReC Engineering & Technical Support

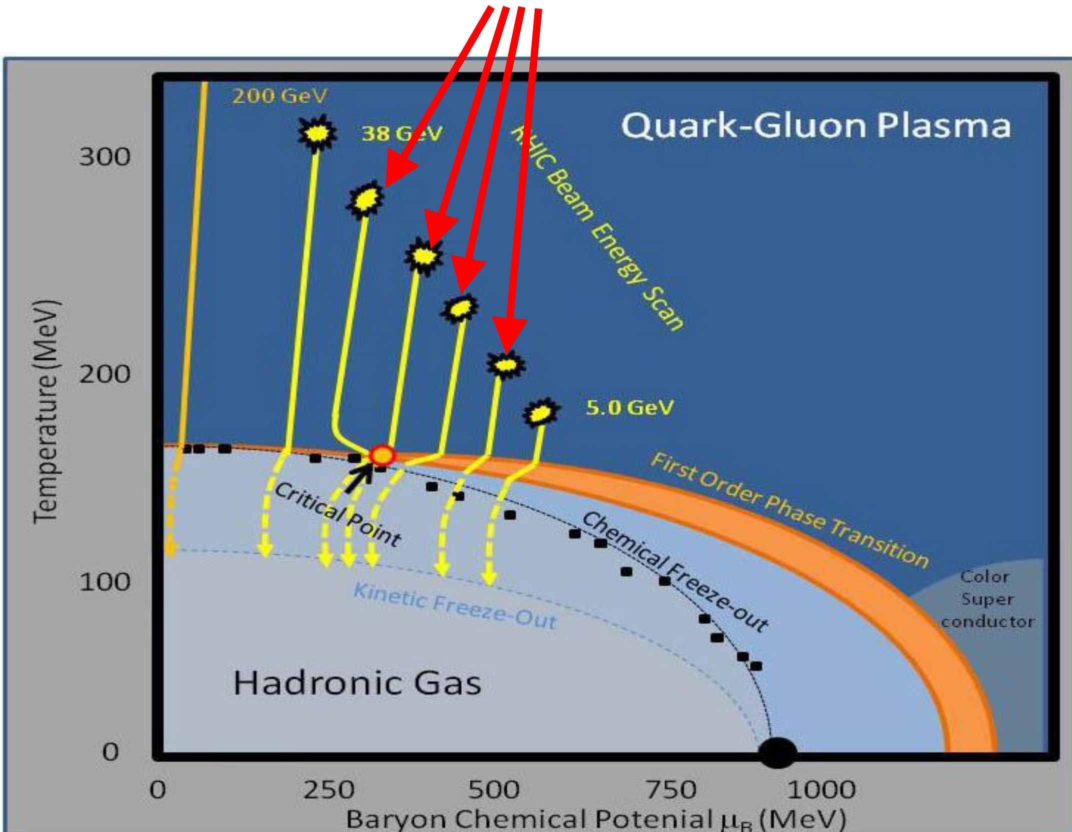


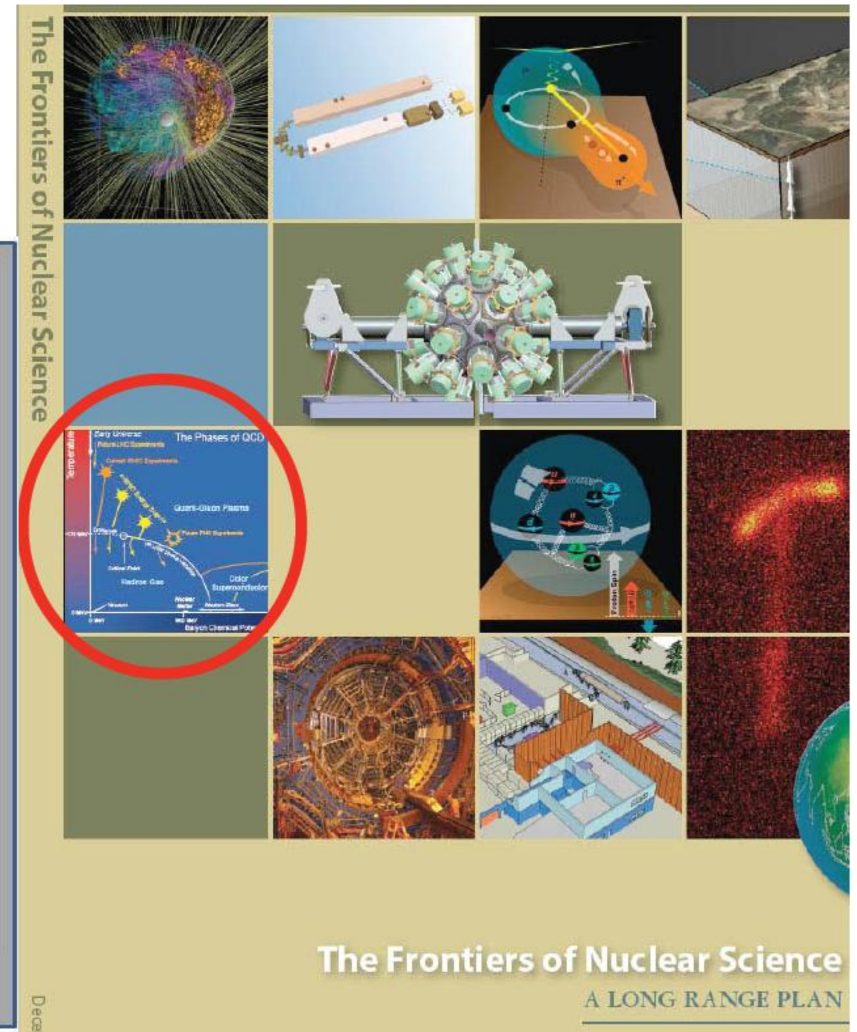
Low Energy RHIC Physics program

Beam Energy Scan I, center of mass energies: $\sqrt{s_{NN}}$ = 5, 6.3, 7.7, 8.8, 11.5, 14.6, 19.6, 27 GeV

(2010 & 2011 & 2014 RHIC runs)

Search for QCD phase transition Critical Point





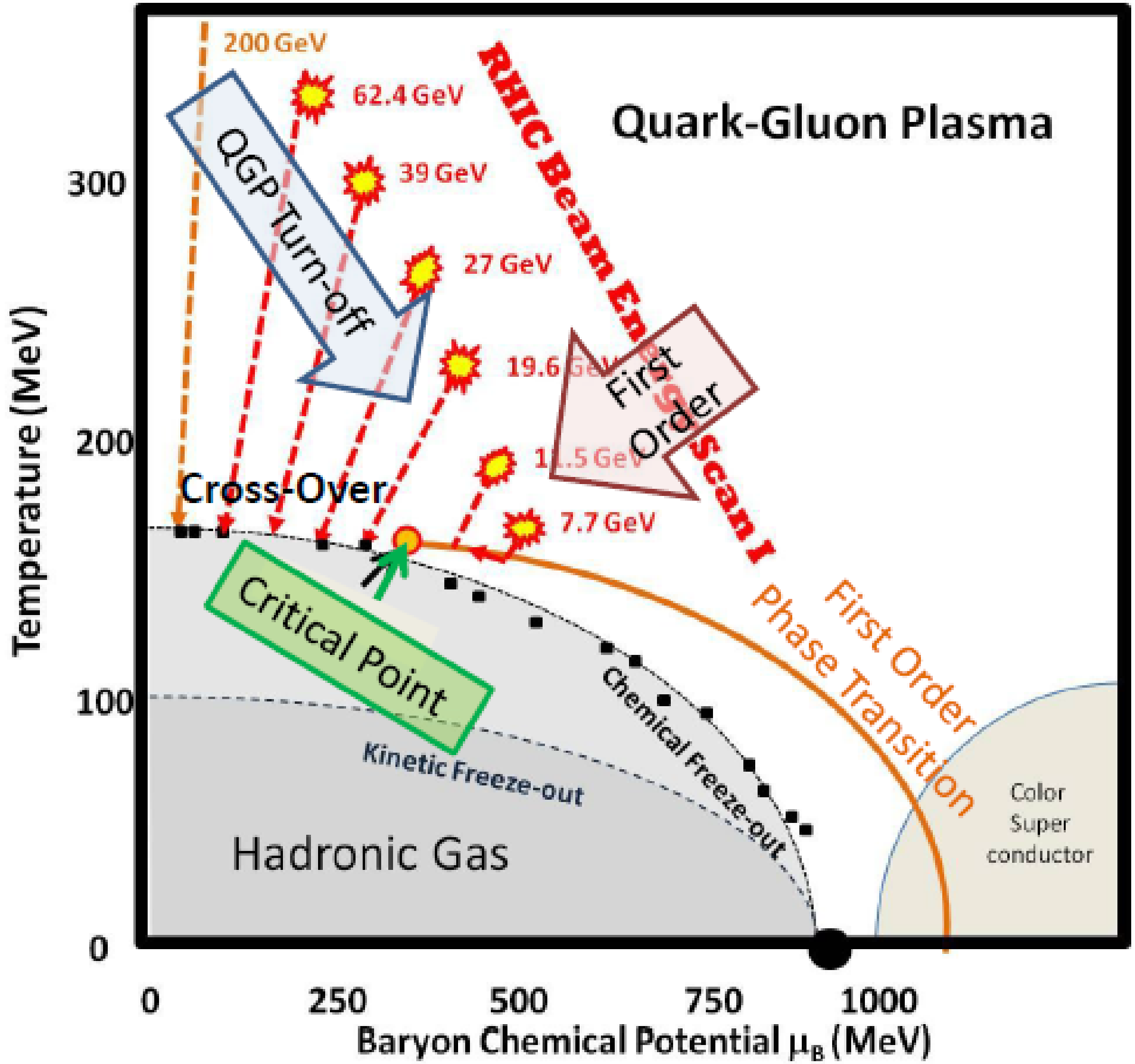
The RHIC Beam Energy Scan I

- We built RHIC to find the QGP.
  And we did it!

- But QGP is a new and complicated phase of matter. We have made huge progress in understanding its nature. At high energy, we expect a **cross-over** transition. At lower energy there should be a **first order** transition and a **critical point.**

- The structure of the QCD matter phase diagram is **fundamental**. This will be in textbooks in future decades

- **Three Goals of BES program:**
  - **Turn-off of QGP signatures**
  - **Find critical point**
  - **First order phase transition.**



Run Schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 500 GeV pol p+p	• Sea quark and gluon polarization	• upgraded pol'd source • STAR HFT test
2014	• 200 GeV Au+Au • 15 GeV Au+Au • Fixed Au target test	• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies • QCD critical point search	• Electron lenses • 56 MHz SRF • full STAR HFT • STAR MTD
2015-2016	• p+p at 200 GeV • p+Au, d+Au, ^{3}He+Au at 200 GeV • High statistics Au+Au	• Extract η/s(T) + constrain initial quantum fluctuations • More heavy flavor studies • Sphaleron tests	• PHENIX MPC-EX • Coherent electron cooling test
2017	• No Run		• Electron cooling upgrade
2018-2019	• 5-20 GeV Au+Au (BES-2)	• Search for QCD critical point and deconfinement onset	• STAR ITPC upgrade
2020	• No Run		
2021-2022	• Long 200 GeV Au+Au w/ upgraded detectors • p+p/d+Au at 200 GeV	• Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism • Color screening for different QQ states	• sPHENIX
2023-24	• No Runs		• Transition to eRHIC

BES Phase II Proposal

BES Phase II is planned for two 22 cryo-week runs in 2018 and 2019

E_{ke} (MeV)	1.6	2.0	2.6	3.5	4.9
$\sqrt{S_{NN}}$ (GeV)	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
μ_B (MeV)	420	370	315	250	205
BES I (MEvts)	4.3	---	11.7	24	36
Rate(MEvts/day)	0.25*	0.6%	1.7*	2.4%	4.5*
BES I $\mathcal{L}$ (1×10^{25}/cm^{2}sec)	0.13	0.5%	1.5	2.1%	4.0
BES II (MEvts)	100	160	230	300	400
eCooling (Factor)	4	4	4	8	15(4)
Required Beam (weeks)	**14**	**9.5**	**5.0**	**2.5**	**3.0+**

Luminosity is especially low at lowest energies.

LEReC-I: 2018

LEReC-II: 2019

Low-energy RHIC operation

Electron cooling (a well known method of increasing phase-space density of hadron beams):

- "cold" electron beam is merged with ion beam which is cooled through Coulomb interactions
- electron beam is renewed and velocity spread of ion beam is reduced in all three planes

requires co-propagating electron beam with the same average velocity as velocity of hadron beam.

Energy scan of interest:

$\sqrt{s_{NN}}$ = 5, 7.7, 9, 11.5, 14.6, 19.6 GeV

At low energies in RHIC luminosity has a very fast drop with energy (from γ^3 to γ^6). As a result, achievable luminosity becomes extremely low for lowest energy points of interest.

However, significant luminosity improvement can be provided with electron cooling applied directly in RHIC at low energies.

To cover all energies of interest need electron accelerator:
$E_{e,kinetic}$=0.9-4.9 MeV

LEReC (2018): 1.6-2 MeV

LEReC energy upgrade (2019): 2-5 MeV

Luminosity with cooling and new RF system

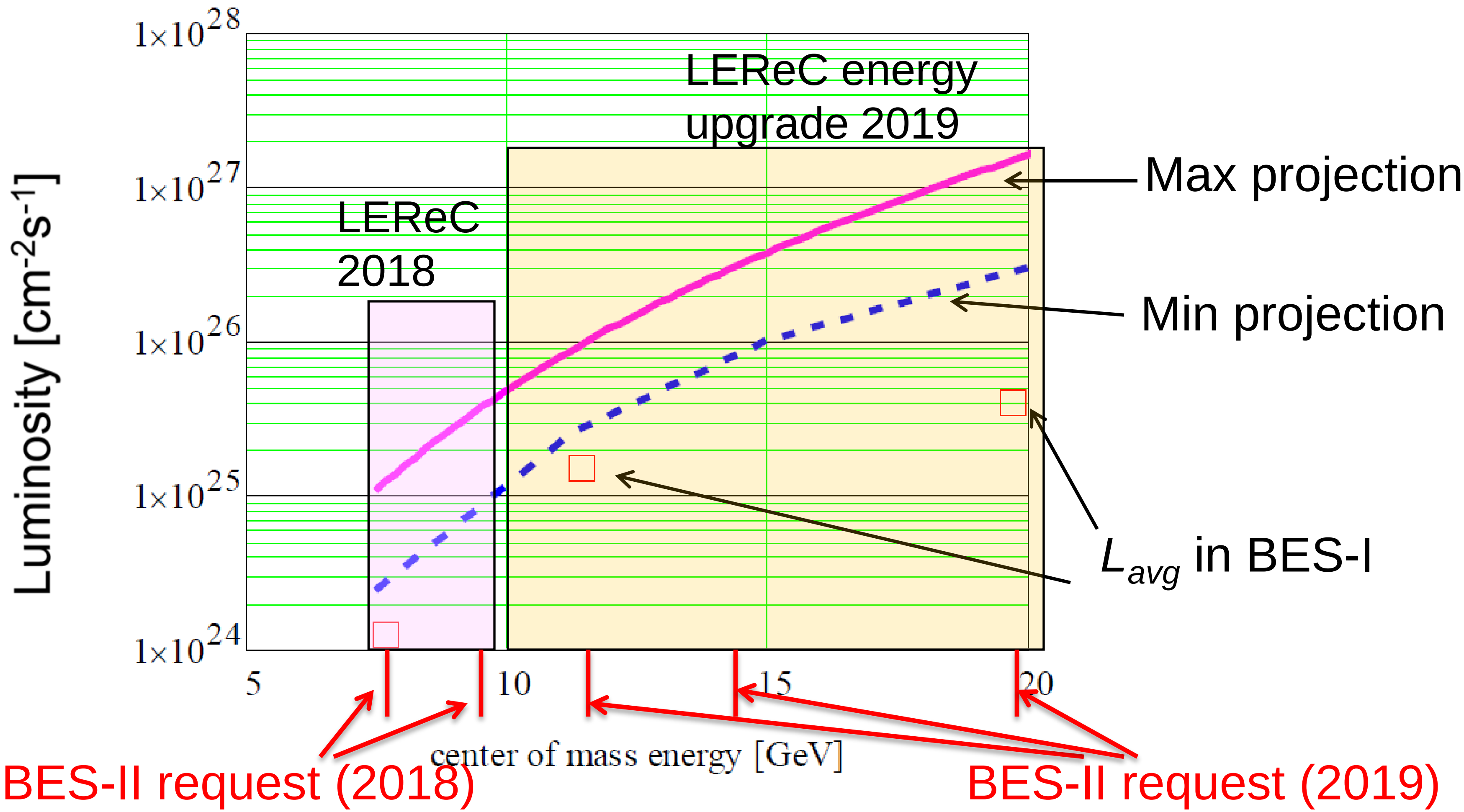


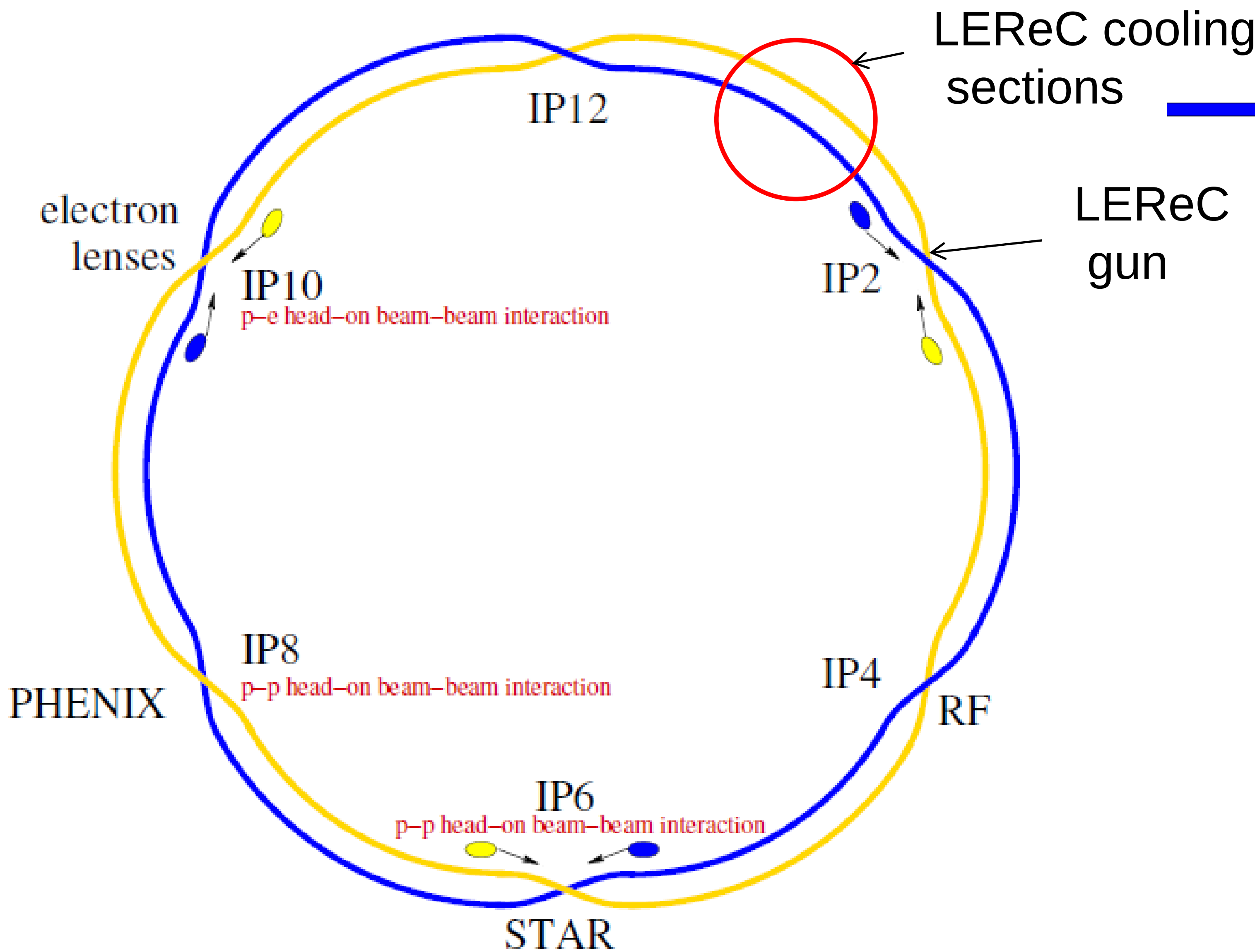
Figure 1. Projection of average store luminosity within +/-1m vertex for 111 bunches of Au ions in RHIC with electron cooling. Red squares: measured average store luminosity in BES-I. Blue dash line: minimum projection of improvement with cooling. Magenta top solid line: maximum projection of luminosity improvement with cooling.

LEReC Project Mission/Purpose

- The purpose of the LEReC is to provide significant luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

- This requires building and commissioning of new state of the art electron accelerator. And commission first bunched beam electron cooler.

- Many new accelerator systems will need to be built, installed and commissioned, including several RF systems, magnets, beam instrumentation, etc.


LEReC cooling sections
LEReC gun
IP12
electron lenses
IP10
p–e head–on beam–beam interaction
IP2
IP8
p–p head–on beam–beam interaction
PHENIX
IP4
RF
IP6
p–p head–on beam–beam interaction
STAR

LEReC scope

- 704 MHz SRF gun with maximum energy of operation 2 MeV or DC gun with the SRF gun used as a booster cavity.
- 704 MHz SRF 5-cell cavity (acceleration to 5 MeV in ERL mode).
- 2.1 GHz (3rd harmonic of the SRF frequency) warm cavity for energy spread correction; 704 MHz warm cavity; 9 MHz warm cavity for beam loading correction.
- Electron beam transport from IP2 region to cooling sections
- Cooling sections in Yellow and Blue RHIC rings – about 20 m long with space-charge compensating solenoids.
- U-turn 180 deg. dipole magnet between cooling section in Yellow and Blue RHIC Rings.

- Electron beam dump.

LEReC-I (1.6-2MeV) and LEReC-II (up to 5MeV) requirements

Ion beam parameters

Full region of energies

Ion beam parameters		
Gamma	4.1	10.7
RMS bunch length	3.2 m	2 m
N_{au}	0.5e9	2e9
I_peak	0.24 A	1.6 A
Frequency	9.1 MHz	9.34 MHz
Beta function@cooling	30 m	30 m
RMS bunch size	4.3 mm	2.7 mm
RMS angular spread	140 urad	90 urad

Electron beam cooler requirement

Electron beam cooler requirement		
Cooling sections	2x20 m	2x20 m
Charge per ion bunch	3 nC (30x100pC)	5.4 nC (18x300pC)
RMS norm. emittance	< 2.5 um	<2 um
Average current	30 mA	50 mA
RMS energy spread	<5e-4	< 5e-4
RMS angular spread	<150 urad	<100 urad

LEReC beam structure in cooling section
Example for γ= 4.1 (E_{ke}=1.6 MeV)

Ions structure:

120 bunches

f_rep=120x75.8347 kHz=9.1 MHz

N_ion=5e8, I_peak=0.24 A

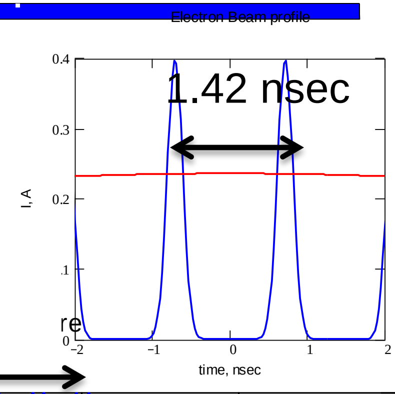
Rms length=3.2 m

Electrons:

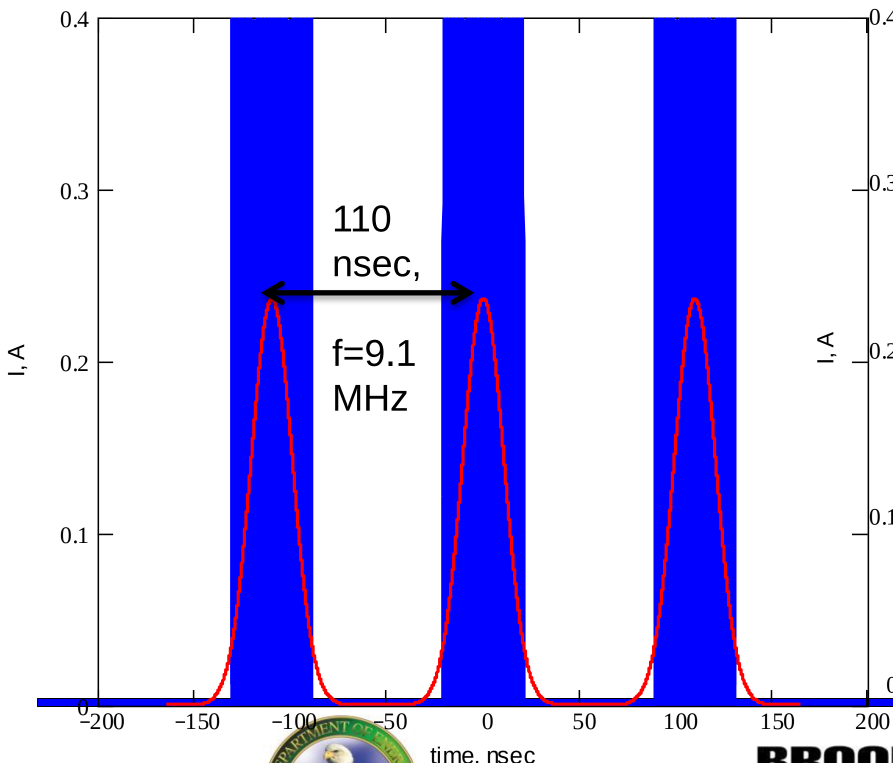
f_SRF=703.518MHz

Rms length=3 cm, I_peak=0.4 A

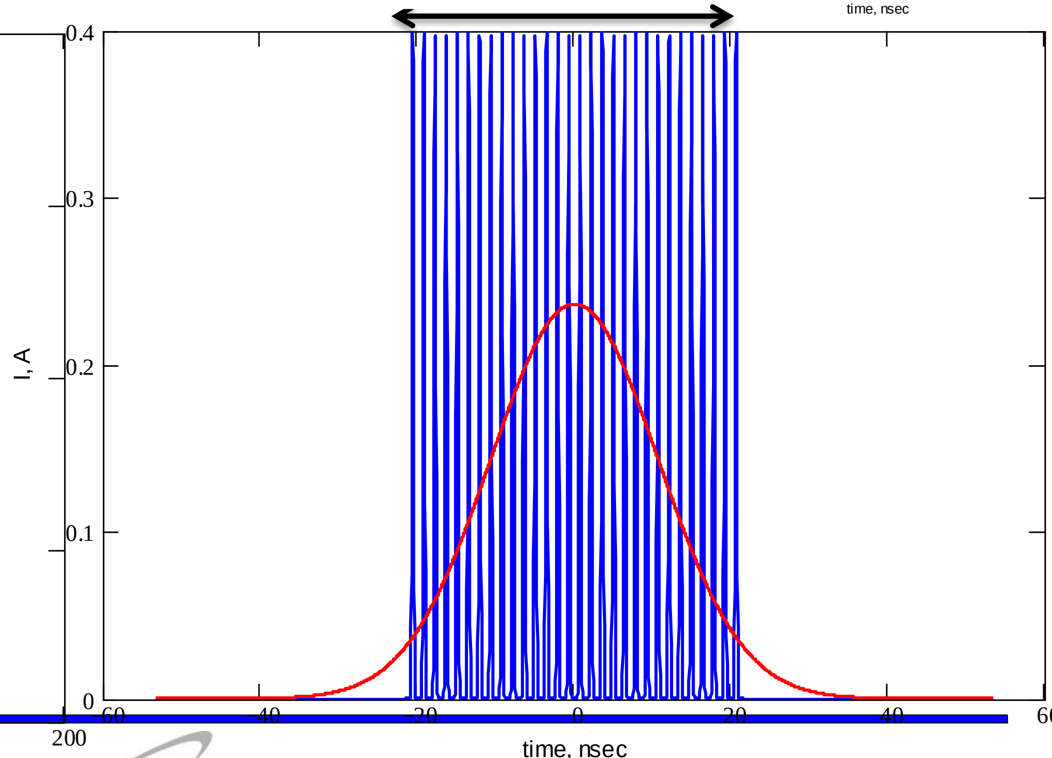
Q_e=100 pC



9 MHz RHIC RF



30 electron bunches



BROOKHAVEN NATIONAL LABORATORY

Office of Science U.S. DEPARTMENT OF ENERGY

December 2014

DOE Review Recommendations

- DOE Technical, Schedule, Cost and Management review took place July 9-11, 2014:

"The LEReC project is aggressive, complex, completely matrixed, high-risk, and high-priority…"

DOE recommendations:
(on Technical design)

Recommendations

- The potential failure of the RF-gun to achieve the required charge/pulse and total current should be assigned and treated as a high risk – done.

- A parallel development path of a DC gun should be pursued. Initiate detailed simulations of the DC gun layout in order to determine the parameters for such a system. Begin collaborations with DC gun experts (at JLab and/or Cornell) as soon as possible to determine costs and timelines for building a DC gun to mitigate the risks of the SRF gun - started

Plan/response
(on Technical design)

- **September-December 2014:** SRF gun beam tests in Bldg. 912
  Goal: demonstration of at least 100pC/1mA by December 2014
  Since goal was not achieved parallel development with DC gun started.

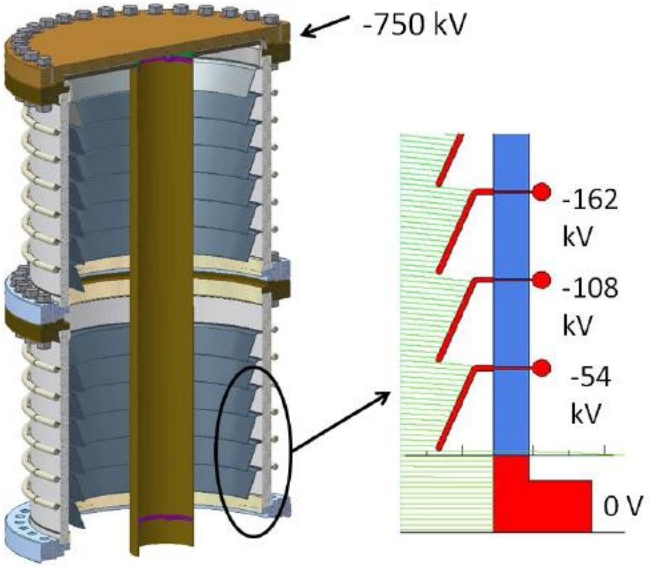
- **February-June 2015**: SRF gun repairs to fix solenoid within the cryostat

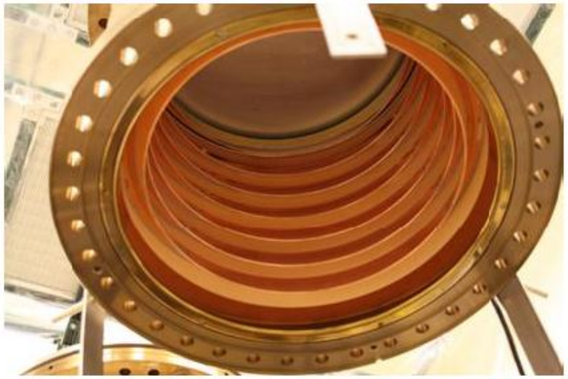
- **Starting July 2015:** beam tests in Bldg.912 with repaired SRF gun, new cathode stalk, new 704MHz LEReC laser system towards CW operation with high-current (goal to demonstrate 50mA needed for LEReC)

- **November 2014:** Collaboration and work on contract with Cornell on DC gun srarted.
  Goal: to have operational DC gun by 2016.

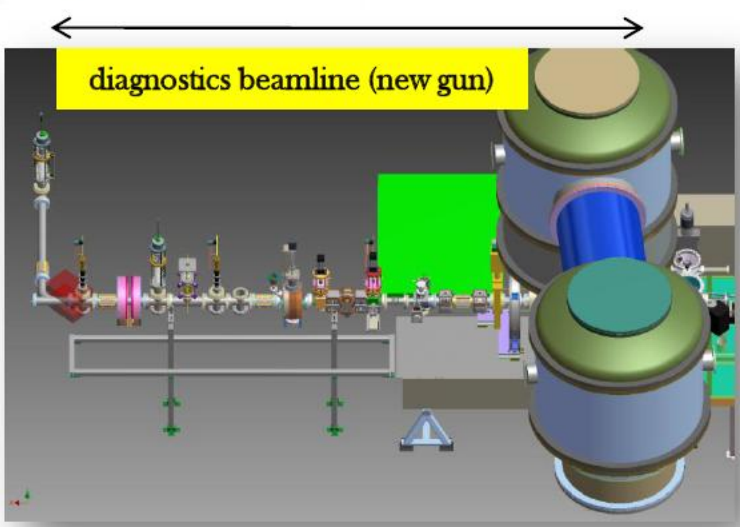
New DC gun

Higher brightness require larger fields at the cathode surface

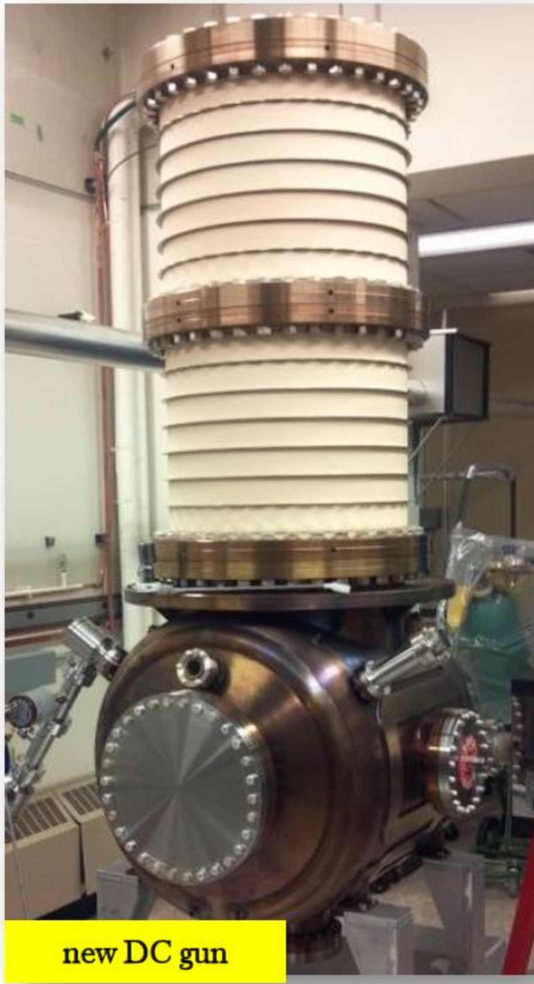




We designed a segmented insulator with intermediate guard rings to catch any field emitted electrons before they reach the insulator material.

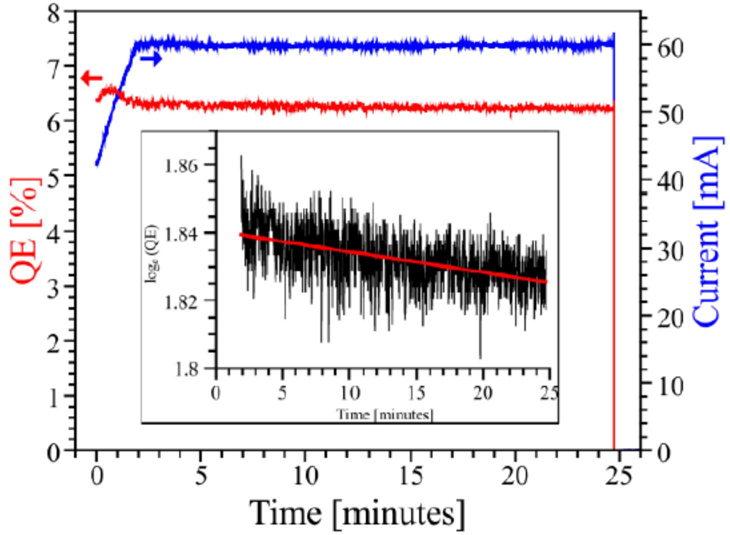


The plan is to have similar gun to be built for LEReC by Cornell (Phase-I of the contract in progress).



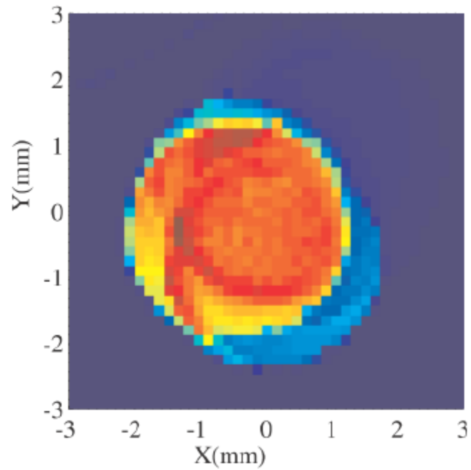
Highest current with CsK_2Sb

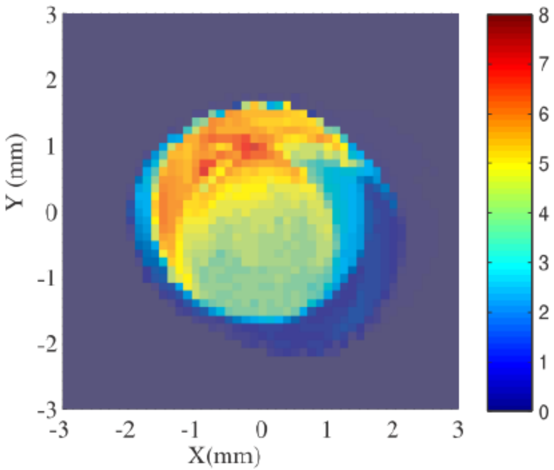
Nov 2, 2012



Using a CsK_2Sb cathode (offset active area), ran at 60 mA for 25 minutes (30 hr 1/e lifetime, this was the longest uninterrupted time span). Went as high as 65 mA for a short time.

Quantum efficiency map of the cathode after growth (left) and after (right) running 60 mA. Delivered over 2000 C from a single 2.5 mm spot.





LEReC DC gun requirements

Operating voltage: 400-500 kV (Cornell)

Charge per bunch (LEReC Phase-1, 2017-18): 100pC (CU)

Average current (LEReC Phase-1, 2017-18): 30mA (CU)

Charge per bunch (LEReC Phase-II, 2018-19): 300pC (CU)

Average current (LEReC, Phase-II, 2018-19): 50mA

Rms normalized emittance < 2 mm mrad for charges up to 300pC (from the gun), CU – demonstrated October 2014

RMS energy spread <2e-4 (from gun/ripple contribution)

Stable 24/7 operation

Cathodes exchanging mechanism for quick cathode replacement without significant delay on operation.

Major accelerator design changes from July 2014 baseline review

- DC gun (Cornell) – parallel path with the SRF gun started.

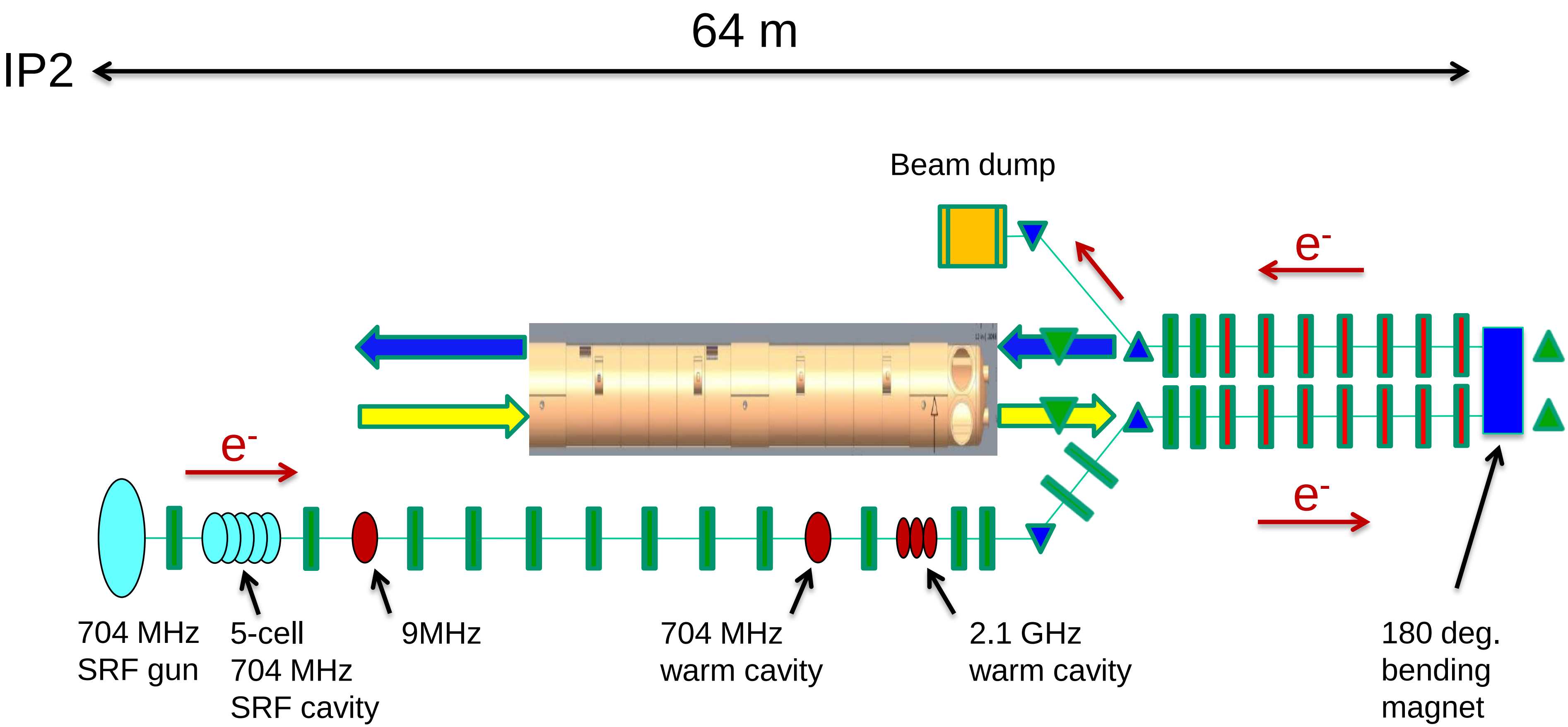
Accelerator design was optimized to be compatible with both guns.

Both gun options will be presented in following presentations.

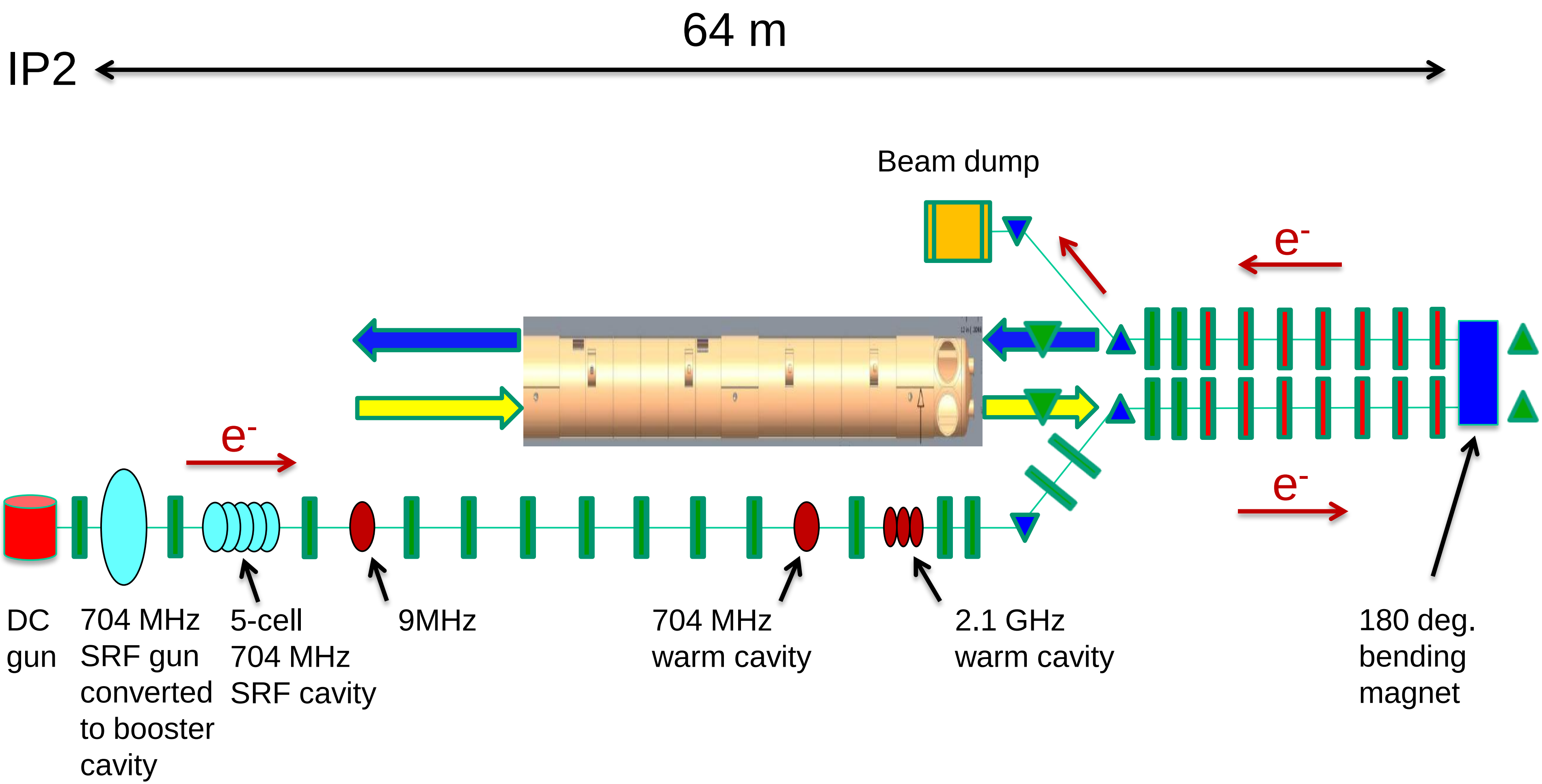
For the DC gun option, SRF gun will be converted to the booster cavity.

- Warm 704 MHz (250kV) RF cavity (LEReC Phase-I, 2MeV).
- Warm 704 MHz (400kV) RF cavity (LEReC Phase-II, 5MeV).
- Warm 2.1 GHz: voltage reduced to 70-100kV
- RHIC 9 MHz bouncer cavity from RHIC.
- U-turn: 180 deg. Dipole instead of two 90 deg. dipoles

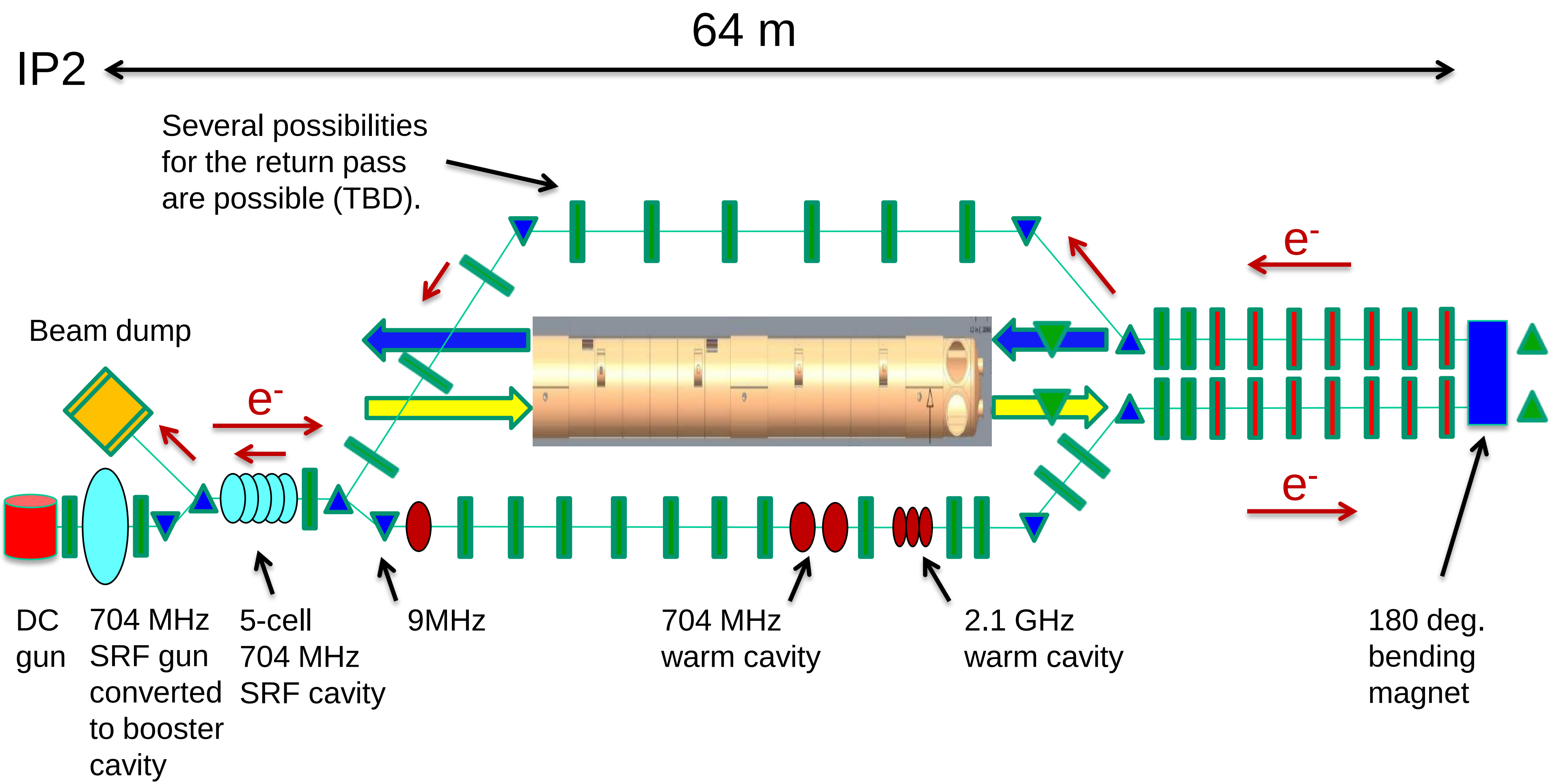
LEReC-I (1.6-2MeV): Gun to dump
SRF gun used as a gun



LEReC-I (1.6-2MeV): Gun to dump
SRF gun used as a booster cavity



LEReC-II (energy upgrade to 5 MeV): ERL mode of operation



LEReC: un-magnetized electron cooling

For LEReC based on RF electron beam continuous magnetic field (in cooling section) is not required.

Un-magnetized friction force:

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln\left(\frac{\rho_{max}}{\rho_{min}}\right) \frac{\vec{V} - \vec{v}_e}{\left|\vec{V} - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

- Un-magnetized cooling:

  very strong dependence on relative angles between electrons and ions.

- Requires strict control of transverse angular spread of electrons in the cooling section.
- Need to keep total contribution (including from emittance, space charge, remnant magnetic fields) to about150 μrad (for γ=4.1).

Scaling:

$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3((\gamma\vartheta_e)^2 + \sigma_{pe}^2 + (\gamma\vartheta_i)^2 + \sigma_{pi}^2)^{3/2}}$$

Requirement on electron angles:
For γ=4.1: σ_p=5e-4; θ<150 μrad

Control of electron angular spread

Example (γ=4.1):

Emittance of 2.5 μm rms: 145 μrad angles (β=30m in cooling section).

We have to keep all other contributions to a minimum. Space-charge defocusing in cooling section is controlled by correction solenoids.

If rms angular spread is 200 μrad -> factor of 2 reduction from optimum cooling with 150 μrad spread.

We have about factor of 1.7 safety margin in current and factor of 1.5 from cooling section length (present length compared to the length used in cooling simulations), so that we could accommodate up to a factor of 2 worse electron beam parameters than optimum (requirements). More than that will result in reduction of maximum luminosity projection.

Electron beam transport

- Bunched beam cooling is a natural approach for high energies.

- For intermediate/low energies, like in LEReC, there are some challenges which has to be carefully addressed:

  - Beam transport of electron bunches without significant degradation of beam emittance and energy spread at low energies:

    Requires stretching electron beam bunches to keep energy spread growth due to the longitudinal space charge to an acceptable level.

  - Keeping low transverse angular spread for the electron beam in the cooling section with a proper engineering design:

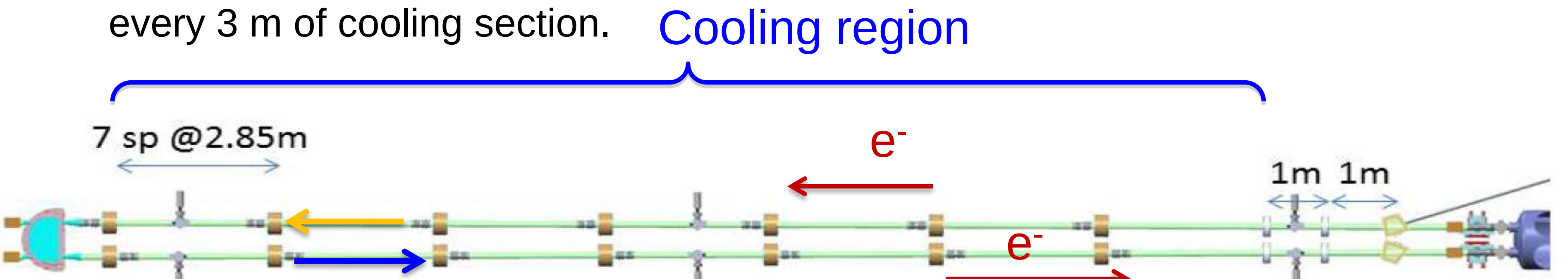
    Correction solenoids and mu-metal shielding.

  - Electron beam with small emittance and energy spread should be provided for several energies of interest.

  - Quality of the beam should be preserved through the entire beam transport and both cooling sections.

Cooling section

- The cooling section is the region where the electron beam overlaps and co-propagates with the ion beam to produce cooling. The electron beam first cools ions in Yellow RHIC ring then it is turned around (U-turn) and cools ions in Blue RHIC ring and then goes to the dump. The electron beam must maintain its good quality all the way through the second cooling section in Blue ring.
- The Blue and Yellow ring cooling sections are about 20 meters each. No recombination suppression is planned. Some space is taken up by matching solenoids, space-charge correction solenoids, steering dipoles and beam position monitors used to keep the electron beam and ion beam in close relative alignment.
- Short (10cm) correction solenoids will be place every 3 m of the cooling section.
- Distance covered by magnetic field from solenoids (200 G) will be lost from cooling. Expect about 40 cm to be lost from cooling from each solenoid, every 3 m of cooling section.



Requirement on magnetic field in the cooling section

γ=4.1:

B_residual=2.5mG ->angles: 35 μrad after L=3m.

Passive (mu-metal shielding) to suppress B_residual to required level (<2.5 mG) in free space between the solenoids.

Distance covered by magnetic field from solenoids (200 G) will be lost from cooling. Expect about 40 cm to be lost from cooling from each solenoid.

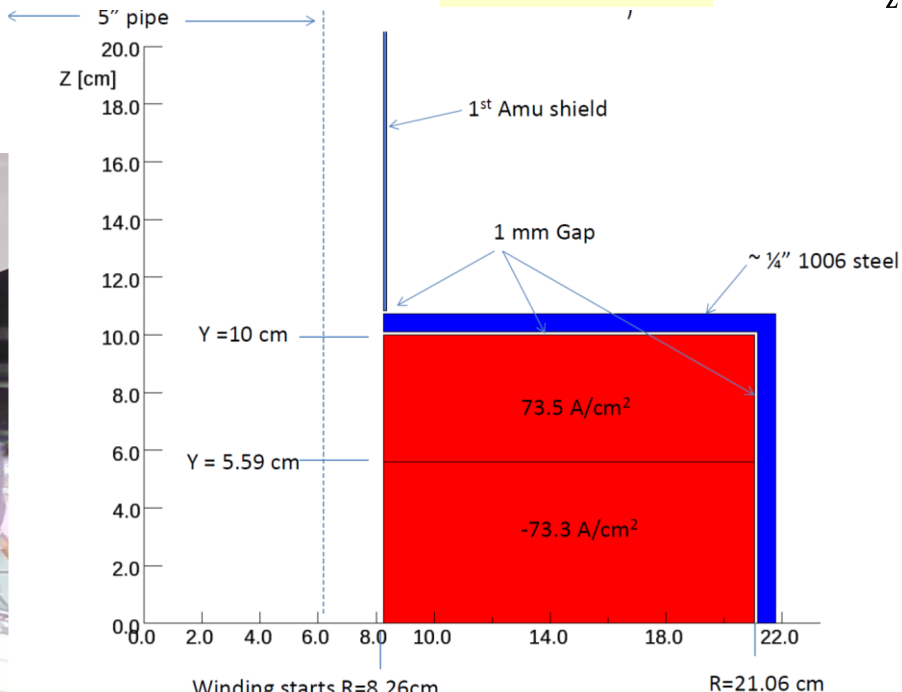
Residual magnetic field from solenoids in cooling region:

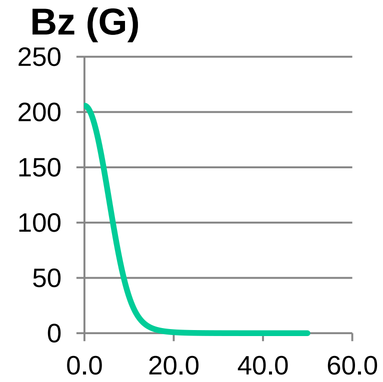
W. Meng

$B_z < 1G$ at z=19 cm

FNAL

shielding





LEReC timeline

SRF gun:

May - Dec 2014: SRF Gun commissioning w/beam (in 912 blockhouse).

January 2015: SRF Gun to dump commissioning w/beam.

February - June 2015: Shutdown for gun modifications and LEReC test preparation (in 912 blockhouse).

Jul 2015 - Jun 2016: High-current commissioning CW mode (LEReC tests in 912)

DC gun:

February - December 2015: DC Gun construction by CU.

January-May 2016: DC gun commissioning at CU.

2015: Installation of cooling sections

July 2016 – March 2017: Move and install Gun, 5 cell cavity , beam dump, cryo, PS, magnets in RHIC

April-June 2017: Systems commissioning (RF, cryogenics, etc.)

July - Sept 2017: LEReC commissioning with e-beam in RHIC tunnel

October 2017: **Run 18, Start commissioning of cooling with Au ion beams**

Upcoming Major Efforts

- Design, request for funding and procurements of “high-priority” items (cooling section magnets and laser)– approved by DOE

- Commissioning of the SRF gun and other LEReC hardware with beam in Bldg. 912. Goals: Demonstrate bunch charges (300pC) and average beam current (50 mA with new LEReC laser) required for LEReC.

- Design, review and contract for the DC gun to be built by Cornell – Phase-I approved (detailed drawings, SOW, RLS, etc.); main contract for construction: February 2015.

- **January 12-13, 2015:** DOE project status review in Germantown.

Summary

- LEReC should provide a significant luminosity improvement for RHIC physics program starting 2018.
- High-priority items are already approved by DOE for procurement (cooling sections elements and new 704 MHz laser which will be commissioned in ERL Bldg. with the SRF gun). Plan is to install cooling sections in RHIC already at the end of 2015.
- DOE project review: January 2015.
- Very tight schedule to meet the goal of installation of LEReC accelerator and transport lines in RHIC tunnel starting July 2016.
- Scheduled project early finish date is September 2017, which would allow start commissioning for physics run in 2018.